UNIQUE FEATURES AND CAPABILITIES OF THE NADS MOTION SYSTEM

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ABSTRACT

Developed by the U.S. National Highway Traffic Safety Administration, the National Advanced Driving Simulator (NADS) has many unique capabilities, including a large excursion envelope motion system with high performance. MTS Systems Corporation was responsible for the manufacture of the thirteen degree of freedom motion system driven by forty-five actuation channels. The motion system features a redundantly actuated ± 10 meter X and Y longitudinal and lateral steel belt drive for high stiffness and smoothness. A Stewart platform hexapod designed for taking advantage of the large X-Y travel rides on top the translation system. The hexapod supports a redundantly actuated ± 330-degree yaw turntable for more effective maneuver simulation and washout coordination. Finally, four high frequency vibration actuators beneath the cab feature self-reaction to minimize vibration to the graphics display dome and the projector support structure. This paper discusses the real-time control and mechanical design solutions that support the high motion envelope capacity of the NADS, including representative performance data.

INTRODUCTION

The National Advanced Driving Simulator (NADS) is the most advanced and capable driving simulator in the world after installation and checkout is completed in the spring of 2001. Under development by the U.S. National Highway Traffic Safety Administration, the NADS will lead research into the human factor aspects of crash avoidance far beyond the automotive test track. The system is located in a facility at the University of Iowa Simulation Center, 2401 Oakdale Boulevard, Iowa City, Iowa (IA) 52242-5003, USA. It is composed of the major subsystems of visual graphics display, vehicle cab instrumentation and control loading, audio sound generation, additional computers for scenario control and vehicle dynamics simulation, and a unique performance envelope motion system.

This paper concerns the design decisions and preliminary performance data for the motion system.

MTS Systems Corporation was responsible for the manufacture and installation of the thirteen degree of freedom motion system driven by forty-five actuation channels. Each of the thirteen degrees of freedom uses newly developed real-time control and mechanical design technologies for the task of driving simulation. The motion system features that are unique to the NADS are: 1) a very long stroke x-y horizontal capability, 2) a custom hexapod (Stewart platform) that complements the x-y long stroke capability, 3) self-reacting higher frequency cab vibration actuators, 4) a ± 330 degree yaw turntable, 5) metal tape translational drives with hydrostatic bearing guides, 6) extensive use of rigid body degree-of-freedom control and tuning with flexible mode force balancing for actuator redundancy, 7) in-depth inverse modeling of known system characteristics for extremely stable high fidelity motion replication, and 8) a multi-level safety system. Figure 1. is an artist's picture of the facility identifying the various degrees of freedom and actuators.

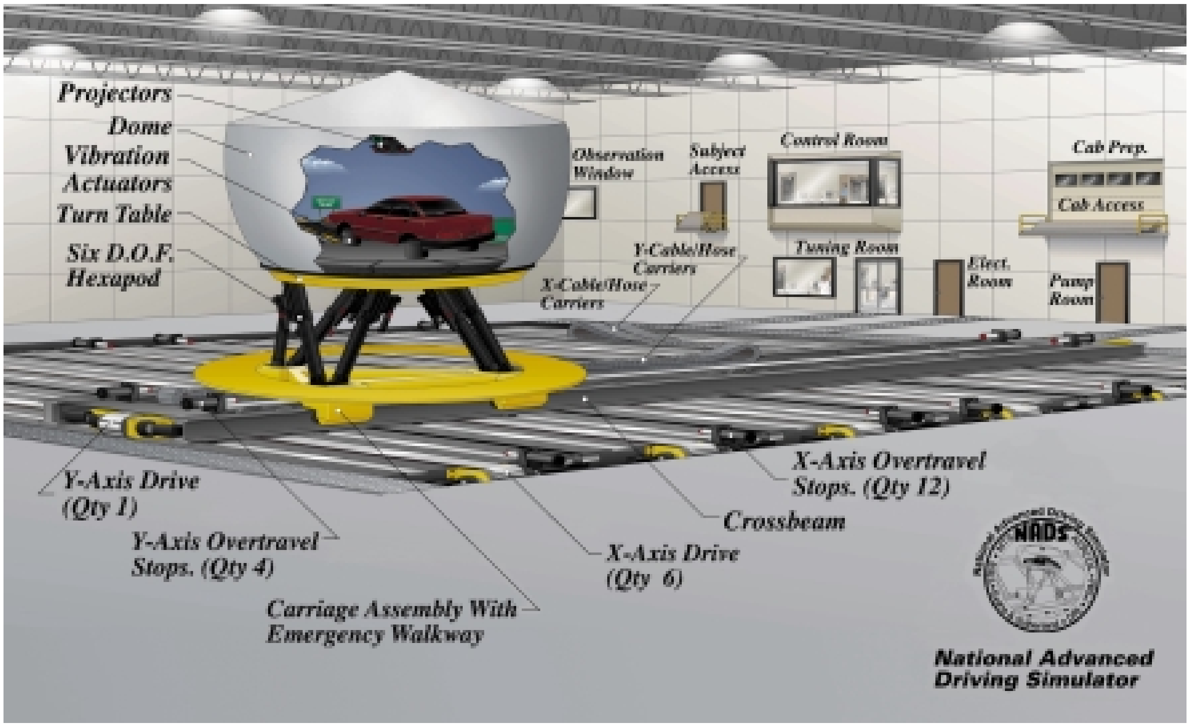

Figure 1. Artist's Conceptual NADS Facility Drawing.

Kinematic Capability

Table 1 gives the kinematic performance capacity specifications. These specifications were determined by the Phase 1 NADS project design, and were influenced by maximizing the motion capacity for a given budget. Preliminary study for the NADS motion base size was done and reported (Garrott, 1994).

Table 1.

Motion Subsystem Component	Specifications		
	D	V	A
	±m	±m/sec	±m/sec/sec
X	10.0	6.1	6.1
Y	10.0	6.1	6.1
Hexapod, Z	0.6	1.5	10.
	±deg	±deg/sec	±deg/sec/sec
Hexapod, Pitch	25.0	45.0	120.0
Hexapod, Roll	25.0	45.0	120.0
Turntable	330.0	60.0	120.0
	±cm	±cm/sec	±kN
Vibration, Z	0.5	20.3	4.5

The NADS X-Y positioner, hexapod, and turntable amplitudes' goal is to provide more realistic motion cues compared with other existing systems for simulating: turning a corner, multiple lane changes, braking to slow down or stop, operating on laterally sloped roads, sustained acceleration and deceleration, severe and sustained cornering, negotiating hills and roadway undulations, rotational spinouts, jack-knifing, collision avoidance maneuvers, wind-gusts, icy and wet roads, and truck passing air buffeting (GAO, United States General Accounting Office Report, 1992).

The NADS vibration actuators goal is to provide more realistic simulations of: wheel-hop, rough road surfaces, running over potholes, running over railroad crossings, running over curbs, running over road joints, running over road edges, sensing vehicle speeds, and running over different road surfaces including concrete, asphalt, gravel, and dirt/sand (GAO, United States General Accounting Office Report, 1992).

Motion System Facility Requirements

The size of the hall where the simulator motion occurs is 35 meters by 35 meters, with an 11 meter clear height (crane rail at 8.6 meter elevation). The foundation size reacting the simulator loads is 27 meters by 28 meters and approximately 1.75 meters thick. The electrical power for the X-Y positioning system (28 electrical motors, each with a 75 kW continuous rating) is about 4,500 kW (peak) with the RMS of typical simulations much lower. The hexapod, vibration and turntable are hydraulically powered by a 1440 liter per minute power supply of 207 bar pressure. The electrical power for this unit is 1,100 kVA at 460 V, three phase, and the cooling water required is 500 liter per minute at 24 degrees C inlet temperature.

Real-time Control Architecture

An important system issue to be solved for the NADS motion system was the software and hardware architecture to effectively control the forty-five actuators with one-hundred-and-sixty feedback transducer signals. Some of these actuation channels are statically and dynamically coupled giving the Motion Subsystem a very complex multi-variable plant to control. Care has been taken to design robust controllers that take into account the highly coupled nature of this system. The real-time software runs on distributed parallel Power PC processors located in four VME chassis. These chassis are connected via a private SCRAMNet link. The graphical user interface runs on a PC running Windows NT. All of the software is written in the MTS Schema™ software environment which features quickly configurable graphical user interfaces and object oriented real-time control classes which support simultaneous rapid prototyping development while running the system(Sparks, 1990). Figure 2 is a diagram showing the overall motion system control architecture.

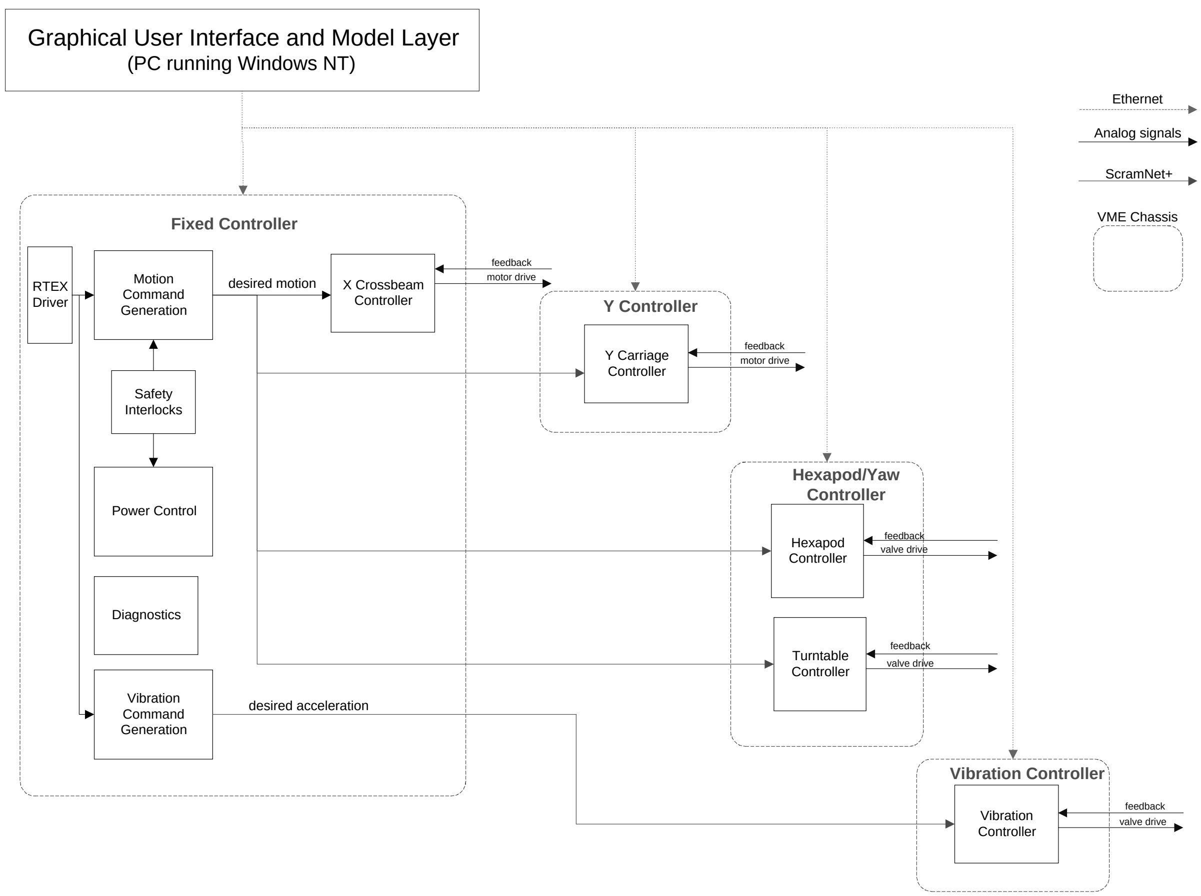

Figure 2. Architecture Figure

X-Y POSITIONER SYSTEM

The X-Y positioner system moves the hexapod in a horizontal plane to simulate horizontal accelerations experienced during cornering, braking and accelerating. Two orthogonal axes provide this motion: a rectangular crossbeam slides along ways in the foundation in the X-axis direction, and the carriage slides along the crossbeam, moving the hexapod in the Y-axis direction. The mass distribution of the NADS system is 10 ton for the hexapod moving mass, 25 ton for the Y degree-of-freedom, and 80 ton for the X degree-of-freedom (cumulative).

Translational Drives

The horizontal drive systems are designed to position the crossbeam and carriage over long strokes, at high velocities and moderate accelerations. They are designed to provide smooth motion with minimal noise and phase lag. A vector induction motor driven metal belt drive system best provides these characteristics. The maximum acceleration noise (RMS) is required to be less than or equal to 20 milli-g.

Seven identical flat metal belt drives are used for X-Y positioner system. The Y-carriage is driven by one belt drive along the crossbeam and X-crossbeam is driven by 6 belt drives working in parallel. Each drive consists of a long stainless steel belt mounted on drums. The driven structure, whether the crossbeam or the carriage, is attached to the belt ends forming a complete loop. Design analysis iterations determined that driving the belt at both ends results in a higher natural frequency. The metal belts offer a stiff drive path and essentially friction free operation over the metal drums. Metal belt drive features:

Smooth operation. Metal belts are free from the pulsation of chordal action often seen in other belt types and chain. This results in precise translation of the control system motion profile.

Wide bandwidth with long stroke. The bandwidth limitation on long stroke positioning systems is the resonant frequency of the moving mass on the spring rate of the drive system. For the metal belt it is the axial stiffness of the pretensioned stainless steel belts. For the required stroke, drive force and velocity, a metal belt drive has approximately 10 times the axial stiffness and 3 times the frequency response of linear hydraulic actuators.

High energy efficiency. Servo motors are much more efficient than servo hydraulics, reducing heat load to the facility as well as service and operational costs.

High strength-to-weight ratio and reduced moving mass. The X drives themselves do not move, only the metal tape moves. In rack and pinion drives or hydraulic actuators a significant mass is added to the moving structure by the drive system.

No lubrication. Unlike links of chain or wire rope, a metal belt is a single element and, therefore, does not generate any component friction that requires lubrication.

X-Y Positioner Controller

The X-crossbeam is equipped with three sensor suites. Each sensor suite consists of an accelerometer and a long stroke displacement sensor. One sensor suite is located on the “left” side of the X-crossbeam, one sensor suite at the X-crossbeam centroid, and one sensor suite on the “right” side of the X-crossbeam. These three sensor suites provide feedback measurements necessary for the X-controller.

The presence of three acceleration and three position sensors facilitate the control of three modes of the X-crossbeam: translation, yaw, and bending. The need for control of these three modes is primarily due to the fact that the rotational inertial properties of the X-crossbeam vary as the Y-carriage moves along the X-crossbeam. Three Variable Control (TVC) is used to control each mode. TVC uses displacement, velocity, and acceleration commands and feedback to give broad band performance.

There are four motors per tape; two on each end. It is important that the motors all work in harmony. This is accomplished by monitoring the force in each side of every tape and monitoring the torque in the motors. Force balance is provided between the ends of each tape and torque balance is provided between each set of motors.

The control of the Y-carriage is similar to the X-crossbeam, but does not require degree of freedom control as there is only one tape. It's topology is the same as the X translational controller and it also includes force and torque balance for the four motors. Preliminary results of the Y-carriage at MTS show good performance with a magnitude variation of less than +/- 2.1 dB and 33 degrees of phase to 3 Hz. Figure 3. shows time history performance to a typical maneuver.

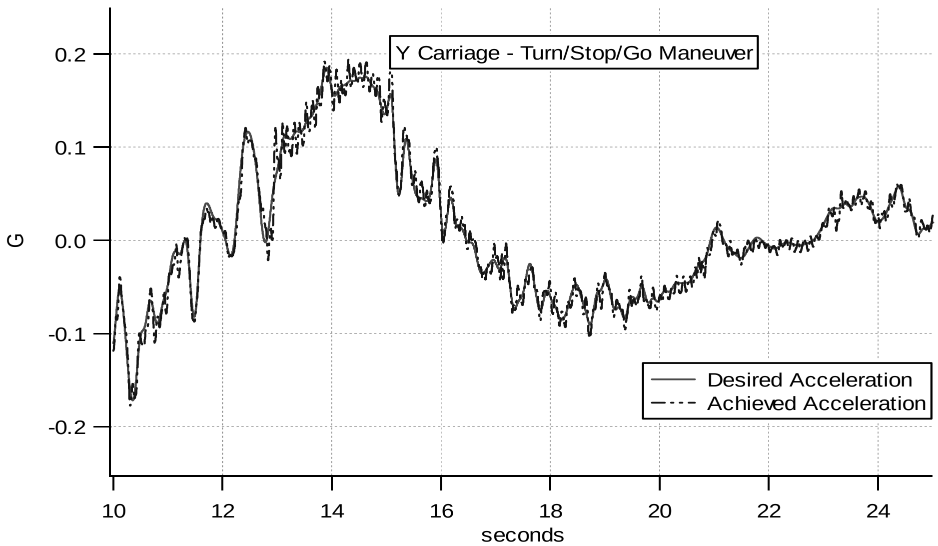

Figure 3. Command and achieved acceleration, Turn-Stop-Go maneuver

HEXAPOD SYSTEM

The hexapod is designed to provide low frequency motion cues in the Pitch, Roll and Vertical axes, as well as transmitting X and Y motion from the X-Y system and reacting Yaw acceleration torque from the turntable drives.

Hexapod actuators

The hexapod consists of six hydraulic actuators arranged in a conventional Stewart platform configuration, however, there are some unique requirements in the NADS system that are met with specific features of this hexapod design:

The actuators are double ended, equal area type. The double ended design provides a wide separation for the hydrostatic rod bearings, giving good lateral stability and stiffness to the actuator assembly. The equal area minimizes pressure switching acceleration distortion, and also reduces the amount of hydraulic fluid flow required. This is particularly important due to the long distribution system.

Each actuator has a separate static support section which partially counterbalances the weight of the platform, dome and payload. This also has the effect of minimizing distortions due to nonlinear hydraulic gains.

The double ended design has a longer overall length for the active stroke provided. This has the effect of minimizing the variation in the Jacobian throughout the working space of the hexapod. Using these longer actuators, a hexapod configuration was developed that meets the system specification requirements and also provides a well behaved system in the sense that there are no singularities, and the only stable settle position is the centered, fully retracted parked position.

The piston area was determined to meet the acceleration requirements, considering the moving mass properties of the system, as well as the desire to have a high oil column stiffness for good control fidelity.

Hexapod controller

The NADS hexapod consists of six hydraulic actuators arranged in a conventional Stewart platform configuration. Each actuator is equipped with a displacement transducer. In addition, the platform and base are each equipped with nine accelerometers. These accelerometers measure translational x, y and z acceleration at three locations on the platform and base.

The displacement and acceleration feedback signals facilitate the control of the hexapod in six degrees of freedom; x, y, z, roll, pitch and yaw. Degree of Freedom (DOF) control is used to attenuate the effects of actuator cross-coupling. Three Variable Control (TVC) is used on each degree of freedom. To provide good acceleration fidelity, the hexapod controller must also reject disturbances arising from the motion of the X-Y positioner and turntable. This is accomplished with a feed-forward controller which anticipates these disturbances and corrects for them (Carmein, 1998). Figure 4 shows the top level data flow of the hexapod controller.

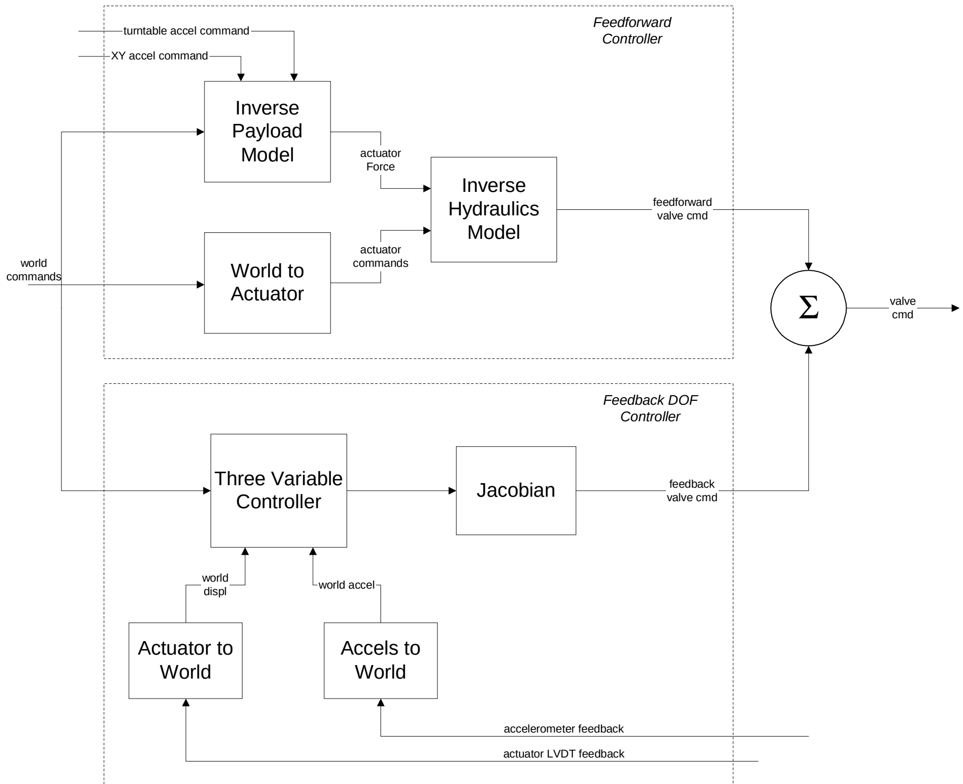

Figure 4. The Hexapod Controller

Degree-of-freedom (world coordinate) commands are used in two parallel paths: a force prediction circuit and a closed loop control circuit. It is to be understood that all signals shown on the data flow diagrams are vector-valued time samples.

The upper part of Figure 4 shows how force prediction is used to anticipate the correct valve opening for each of the actuators. Predicting the valve opening gives the controller an accurate feed-forward control signal. Feed forward greatly reduces the need for high-gain feedback control and also reduces the phase delay of the controller. Delay in the motion controller must not exceed the frame update rate in the video system or the driver will sense the desynchronization of motion and video events.

The lower part of Figure 4 shows the closed-loop servo control required to stabilize the hydraulic system. Closed loop control is done in degree-of-freedom (world) coordinates. The three variable controller block uses three command signals and three feedback signals on each of the six channels: (X, Y, Z, Roll, Pitch, Yaw) The three components are position, velocity and acceleration. Position feedback is most effective at low frequencies where the position transducers will have high resolution over the range of motion. Acceleration signals are largest and most effective at high frequencies where the position transducers would be limited to a few bits of resolution.

Figure 5 shows the internal view of the Inverse Payload Model shown as a component of Figure 4.

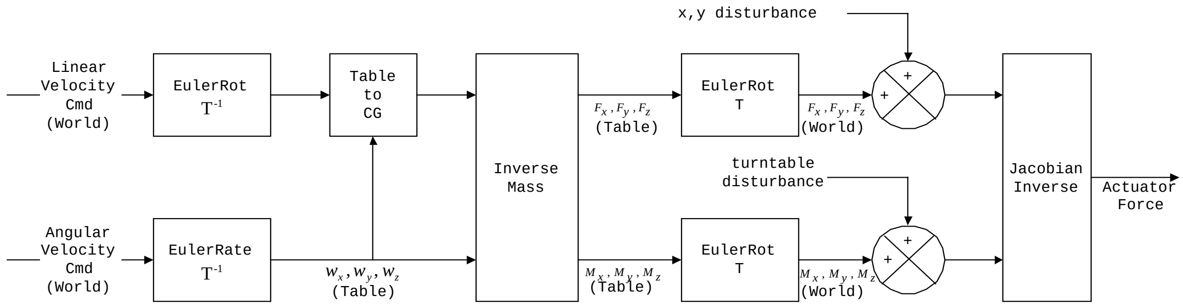

Figure 5. Inverse Payload

The Inverse Payload predicts the actuator forces required to follow the required DOF trajectory. The components shown on this figure are instances of low-level Schema classes.

The *EulerRot* object transforms the world linear velocity vector (derivatives of x, y, z) into the table-centroid system velocity. The *Table to CG* object transforms the centroid velocity into payload center of gravity velocity. The *EulerRate* object transforms world angular velocity commands (Euler-angle derivatives) into payload body rates.

The set of payload velocities and body rates are connected to the *InverseMass* object, which calculates the forces and moments required to move the payload. These forces and moments are then transformed back into world coordinates by the inverse *EulerRot* and *EulerRate* objects. Finally, the *JacobianInverse* object converts the world forces and moments to a vector of individual actuator forces.

The *EulerRot*, *EulerRate* and *JacobianInverse* are implemented as pairs of objects. The objects shown on the diagram are all instances of the class *VectorTransform*, which multiplies an input vector by a matrix to obtain the vector output. The matrix components are themselves dynamic signals computed by instances of class *EulerRot*, *EulerRate* and *Jacobian*. This is done so that multiple *VectorTranform* objects can share the current value of a computed matrix.

Preliminary results of the hexapod control taken at MTS show good performance with a magnitude variation of less than +/- 2.7 dB and 28 degrees of phase to 3 Hz. Figure 6 shows time history performance of the hexapod Z acceleration to a typical maneuver.

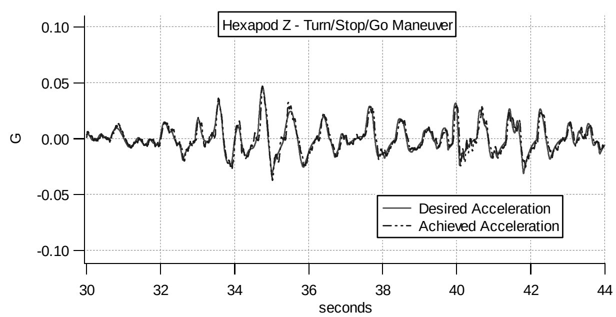

Figure 6. Hexapod Z command and achieved acceleration, Turn-Stop-Go maneuver

TURNTABLE

The Yaw Turntable belt drive system rotates the yaw turntable and the platform to provide large angle rotation cue capability to take maximum advantage of the long lateral excursions.

Hydraulic motors and planetary gear reducers

Three hydraulic motors were selected for yaw drive because they have much higher power density characteristics than electric servo motors. The axial vane hydraulic motor selected has superior smoothness compared with other type of hydraulic motors, particularly during starts and slow-speed operation. Smoothness, high stiffness, and low acceleration noise in all four quadrants of power transmission were the dominant requirements that led to the selection of the planetary gear drives. The averaging effect of a multiple mesh planetary gear set actually reduces gear tooth manufacturing errors. Key features of the design are:

360° pressure balanced rotor. The diametrical clearance between the vanes and housing is fixed and there is no metal-to-metal contact. As a result they have very low torque and speed ripple and low breakaway pressure.

Rigid one-piece rotor and shaft construction with no internal backlash provides high torsional stiffness of the motor.

High starting torque

Compact Size - A planetary gear drive offers a significant saving in size and weight when compared to conventional gear drives.

Highest Efficiency - Close machining tolerances on all components provide a mechanical efficiency of up to 99% per reduction.

Low Noise Level - Close tolerances on all internal components combine with a sturdy housing provide a very low noise level (average of 70 dBA at 3 feet under no load).

Reversing Service - The combination of minimum backlash, low inertia, and high radial and torsional stiffness make planetary gear drive a good choice for reversing service applications.

Turntable controller

The command input to the turntable controller is a desired angular acceleration; feedback to the controller consists of turntable angular position (rotary encoder) feedback, turntable rotational velocity (tachometer), and three differential pressure signals (one differential pressure per hydraulic motor).

To ensure smooth performance of the turntable, the three hydraulic motors must act in unison. Three Variable Control (TVC) is used in the outer loop to track commanded angular accelerations; torque balance is used in the inner loop to ensure that the hydraulic motors work together.

VIBRATION SYSTEM

Hydraulic Actuators

The design consists of two coaxially mounted, independently controlled hydraulic actuators attached to a structural housing and base. The upper actuator provides high frequency input to the vehicle cab. The lower actuator is physically coupled to the upper actuator through the housing and acts as an inertial force generator, minimizing load transfer to the hexapod platform. Overall actuator assembly weight is 91 kg. Pre-loaded transfer balls mounted in the base of the housing allow the vibration actuator assembly to be moved easily during set up of cabs.

Vibration Controller

The sensor suite for each Vibration assembly contains two displacement transducers (one for each actuator), three accelerometers, two delta pressure transducers, and a force cell. These components are combined on four assemblies to create eight control loops. In a vibration assembly, two actuators are configured opposing each other. The upper actuator is connected to the cab vehicle while the lower actuator reacts against the upper actuator vibrations to minimize the forces generated into the platform.

Figure 7 is a picture of the mechanical hardware and control elements. The triangles "Vibration Actuator Controller" and "Reaction Actuator Controller" are simplified versions of the data flow diagram for the closed loop discussed above. As Figure 7 shows, the vibration actuator controller receives the acceleration command and uses the accelerometer and LVDT for its acceleration and displacement feedback to generate a command for the vibration servovalve. The reaction actuator controller uses the force exerted on the cab to generate an acceleration command. The reaction actuator controller moves the reaction mass to counteract the effects of the cab to minimize the disturbances into platform and vision system.

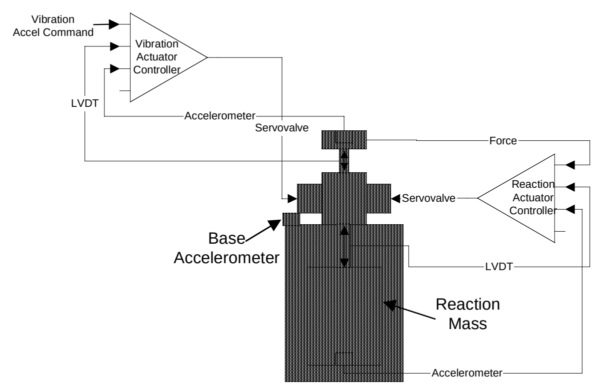

Figure 7. Vibration Mechanical Hardware and Control Elements

Preliminary results at MTS show flat response of the vibration actuators to 20 Hz and a reduction in base acceleration as a result of active cancellation to –11 dB of the uncanceled base acceleration.

CONCLUSIONS

Current Status

The NADS will provide the world with a new driving simulation capability. In addition to the use of the simulator for realistic scenarios for the human-driver-in-the-loop mission, the NADS will be used to research standards and scale factor effects for other driving simulator designs because of the available Partial integration tests including visual graphics, the cab with control loaders and instrumentation, the audio system, and host computer with vehicle dynamics and scenario control are being conducted.

Additional data for a lane change maneuver and a braking maneuver is shown in Figures 8 and 9. There is good correlation between the vehicle dynamic model specific force and that physically experienced by the simulator test subject driver. Figure 10 is a photograph of the partial integration test system at MTS with a Ford Taurus as the subject vehicle cab. The data presented in this paper was taken with the system in the photograph.

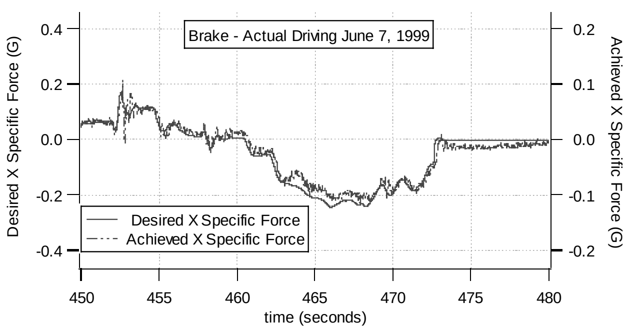

Figure 8. Braking Simulator Performance

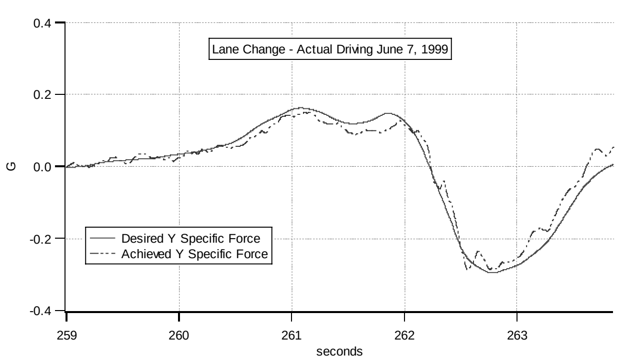

Figure 9. Lane Change Simulator Performance

motion performance envelope. For example, more data can be obtained on the causes and reduction of simulator sickness, which is a key issue limiting some applications.

The Y-carriage, the hexapod, the turntable, and the vibration actuators were integrated and checkout and demonstration testing was performed at MTS.

Figure 10. Partial system integration test configuration at MTS

The installation at the University of Iowa including the X-crossbeam and drives was completed in 2000, and the system is planned to be complete and operational in the spring of 2001. Figure 11 shows a photograph of the installed system.

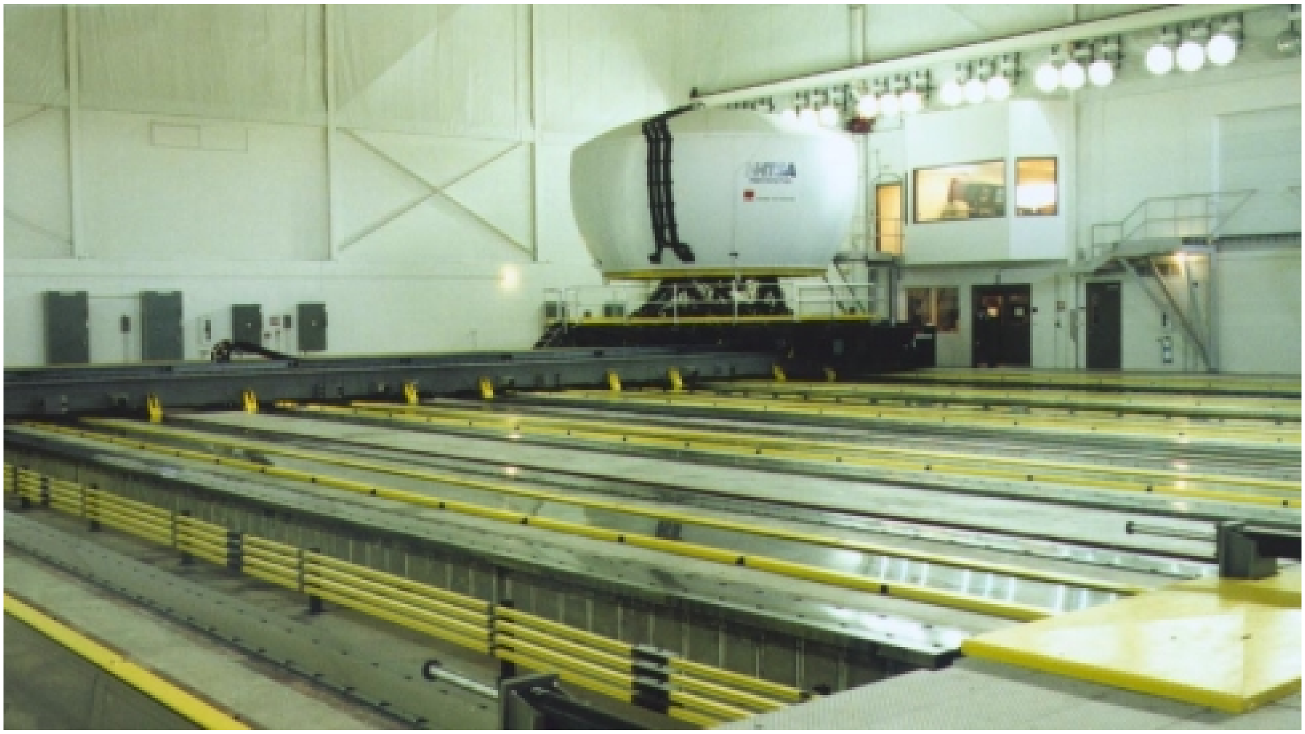

Figure 11. Installed NHTSA NADS at the Univeristy of Iowa

Acknowledgements

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